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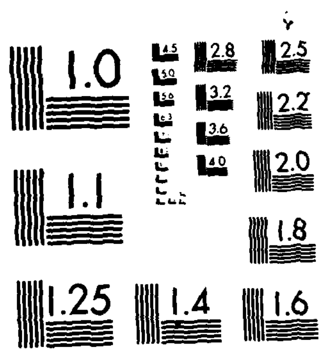

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MELBOURNE, VICTORIA

Aerodynamics Technical Memorandum 381

ROTOR WAKE MODELLING METHODS SURVEYED DURING AN OVERSEAS VISIT

by

K. R. REDDY

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SUMMARY

Between 8th September and 9th October 1985 the author attended the Eleventh European Rotorcraft Forum in London, and visited ten research Establishments in England, West Germany, and the USA. The main purpose of the overseas visit was to investigate rotor wake modelling methods currently used. A report is given on the Forum attendance and discussions held at the establishments, together with a general review of rotor wake modelling.

POSTAL ADDRESS: Director, Aeronautical Research Laboratories,
P.O. Box 4331, Melbourne, Victoria, 3001, Australia.

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1. INTRODUCTION

The author attended the Eleventh European Rotorcraft Forum in London on 10-13 September 1985. Following this, visits were made to ten research establishments in England, West Germany, and the USA. These include Southampton University, Westland Helicopters, RAE Farnborough, MBB Munich, UTRC (Sikorsky) Hartford, Boeing Vertol, NASA Langley, Hughes Helicopters, and NASA Ames. Full address and contacts are listed in Appendix A. The reception at all establishments was friendly and cooperative. Discussions were held on a variety of subjects of interest and the opportunity was taken to inspect test facilities. Visits to RAE Farnborough and NASA Ames were organized with cooperation of the respective TTCP HTP-6 national leaders. In reporting on the overseas visit, the opportunity has been taken to review the overall subject of rotor wake modelling methods, which is the author's own area of interest that was pursued in discussions held.

A detailed knowledge of the non-uniform inflow at the rotor is essential to calculate reasonable estimates in the areas of rotor performance, vibration, blade stress, rotorcraft stability and control, and acoustics[1]. The velocity field in the vicinity of the helicopter is also needed in the calculation of aerodynamic forces on the helicopter fuselage, attached weapons, and any other externally slung bodies[2]. Calculation of the rotor wake geometry and resulting induced flow field still remains one of the most important, but difficult, problems for the rotary wing aerodynamicist. The advent of the high speed, electronic, digital computer has made possible the adoption of the straight forward approach of tracing the vortex filaments trailed by each blade. In this document, the development of complex and computationally demanding wake methods is described, and the present trend towards simpler wake models is noted. Two wake related problems, namely the interaction of a tip vortex with the following blade, and the interaction of the rotor wake with the ground (known as ground effect) are also discussed.

2. ELEVENTH EUROPEAN ROTORCRAFT FORUM

The European Rotorcraft Forum is one of the most important meetings for reporting helicopter related research and development. Over 300 delegates

from 18 countries attended the Forum, including many prominent members from the USA and Europe. The technical papers presented at the meeting covered a wide range of topics, including aerodynamics, blade dynamics, acoustics, flight mechanics, and aircraft design. A total of about 100 papers were presented covering the above areas of research. Papers relevant to rotorcraft wake modelling methods are discussed here.

H. Zimmer presented a paper[3] dealing with the blade load calculations and performance estimation of co-axial rotors and propellers using a prescribed wake geometry. Here, Zimmer uses short vortex filaments to represent the near wake and a single tip vortex to represent the far wake of a blade. Calculated performance estimates agree well with the measurements. However, there is some doubt about the position of the tip vortex when it first encounters the following blade. Because of wake impingement, the second rotor is less efficient, developing only 80% of the thrust developed by the first rotor.

David Clark presented a paper[4] explaining the basic capabilities of the computer program VSAERO (Vortex Separation Aerodynamics). The program combines the modelling capability of rotor wake models and panel methods, the latter including the determination and representation of regions of separated flow. As a consequence, in addition to determining the effect of fuselage and wing induced disturbance on the rotor, the program could also be used to determine the effect of rotor downwash on the fuselage and other components (e.g. wing and horizontal and vertical stabilizers). To test the validity of the modelling techniques employed, the program was used to study the interaction of a tilt-propeller and a wing combination. The calculated results were claimed to be in excellent agreement with NASA measurements on a model rotor.

D. Favier presented a paper[5] emphasizing the inadequacy of the present wake geometry calculations in modelling the far wake. In this paper, the free wake analysis is used for the near region i.e. $0 \leq \Psi \leq 2\pi/b$ (where Ψ is azimuth angle and b number of blades). A prescribed wake model of the type used by either Kocurek and Tangler or Landgrebe is used in the region $2\pi/b \leq \Psi < 5\pi/b$. For $\Psi \geq 5\pi/b$, experiments indicate that some vortex instabilities start to appear, while a very small wake contraction is observed. Based on this observation, a helical wake geometry with constant pitch is used for $5\pi/b \leq \Psi < 10\pi/b$. For the last region, $\Psi \geq 10\pi/b$, the wake exhibits strong

vortex instabilities, and a semi-infinite cylinder with constant vorticity distribution is used. Results obtained using this wake model are compared with those using the model of Kocurek and Tangler[9], which uses a vortex ring to represent the unstable far wake. The vortex ring has a radius equal to that of the rotor radius, and an intensity four times the tip vortex strength. The paper concludes that the semi-infinite vortex cylinder model for the far wake region provides better correlation with the measured blade load distribution. However, it must be remembered that Kocurek and Tangler did point out that the choice of vortex ring location and strength were arbitrary. Hence, it may be possible to produce an effect similar to that obtained by Favier using a different combination of the above parameters.

3. ROTOR WAKE MODELS

Many aerodynamicists working in academic institutions, research organizations, and the helicopter industry have contributed either directly or indirectly during the past thirty years in the continual development of rotor wake models. The account given here on rotor wake modelling methods is intended to place the current work in the context of the present wake models used by helicopter researchers visited by the author. A more general survey of the literature for the period prior to 1972 can be found in Reference 6.

Experimental investigators using earlier smoke-visualization data and more recent laser velocity measurements have shed much light on the behaviour of vortex flow in the wake of a helicopter rotor. Based on experimental data, Gray produced the classical picture (shown in Figure 1) describing the motion of the helical vortex shed from a single bladed, hovering, model helicopter rotor. Even though the picture was aimed primarily at describing hovering flight, a strong tip vortex and the inboard vortex sheet containing the components of trailing and shed vorticity are important elements that exist in every flight condition. The strength and the geometric distribution of these vortex elements will vary with flight condition.

The rotor wake geometry presented in Figure 1 first appeared in a Princeton University report in 1955[7]. Since then, there have been many attempts to develop computational models with the basic vortex elements appearing in Gray's schematic sketch representing the experimental results. The rotor wake

consists of the trailing vorticity, due to radial variation of blade circulation, and the shed vorticity, due to azimuthal variation of blade circulation. Because blade lift and circulation are concentrated at the tip, the strength of the trailing vorticity is high at the outer edge of the rotor wake. This vorticity rolls up into a concentrated tip vortex. The inboard portion of the vortex sheet contains both trailing and shed vorticity. Since the gradient of bound circulation, both radially and azimuthally inboard of the blade tip, is low, vorticity in the inboard vortex sheet is much weaker and more diffuse than at the tip. If the distribution of this vorticity is known, then the velocity field at any point can be calculated using the Biot-Savart law.

The development of complex helical wake models and simple wake models based on vortex line or vortex ring geometry is presented below.

3.1 Complex Helical Wake Geometry Models

The main task is to determine the geometrical distribution of vorticity in the rotor wake. The vortex sheet is modelled by assuming that its influence can be approximated by using discrete vortex filaments of appropriate strength positioned in the plane of the sheet, as shown in figure 2. The calculation of the wake geometry would involve the computation of the distortion of these vortex filaments due to their own induced velocities and those due to the motion of the rotorcraft. As a part of the computational procedure, the vortex elements are broken into convenient straight line segments. These segments are chosen to be sufficiently small that, for purposes of computation of the wake-induced velocities, they may be considered as vorticities with constant or linearly varying circulation along their length. The wake configuration at any instant is then defined by the location of these vortex filaments. Each vortex filament has a length (L), core radius (a), and strength (Γ). Given these, the Biot-Savart relation can be used to calculate the induced velocity at any point.

In the free wake method, the computation is accomplished by the following iterative procedure. The initial wake geometry is first specified, usually as either an undistorted helical shape or distorted wake geometry based on experimental data. The velocity contributions of all vortex elements are calculated at each reference point (end points of vortex filaments). Then these points are allowed to propagate with the computed velocity over a small

increment in time, generating a new vortex geometry. This process is repeated until the wake converges. Using the converged wake, the induced velocity can be calculated at any specified point, again applying the Biot-Savart relation.

The above wake model forms the basis for many wake models that are in current use. Retaining all the wake elements and extending the model far below the rotor would present a formidable computational problem, since every vortex element is influenced by, and influences, every other element. This form of rotor wake representation is one of the most complex, and consequently is normally prohibitively expensive to run.

A further simplification of the rotor wake geometry is valid if certain approximations are introduced. The wake behind the blade is divided into various zones or regions of importance. These are usually named as near, far, and distant wake regions. In many cases, the far and distant wake regions are merged. However, in order either to simplify the computational process[8] or improve the correlation between the calculated results and flight measurements[9], a different model for the distant wake is sometimes adopted. Here, the discussion is mainly restricted to the two-zone wake model, which is shown in Figure 2. The near wake region contains that portion of the wake leaving the reference blade up to its first encounter with the following blade. The far wake region extends beyond the first encounter through three or more spirals.

Just behind the reference blade, detailed radial and azimuthal variation of the wake vorticity is important, because most of the contribution for the induced velocity comes from this portion of the wake. Hence, for the near wake of the blade, the full vortex mesh representation is retained. The far wake model consists of trailing vortices only, as shown in Figure 3. It is known that the strength of the shed vorticity is small in comparison to the trailing vorticity. Hence, the contribution of shed vorticity in the far wake could be neglected in the wake geometry calculations. The commencing locations, circulations, and core sizes of the trailing vortices in the modified wake are determined in terms of the final values of the full mesh wake. The wake induced velocities, wake distortions, and other calculations are essentially the same for both the near full mesh wake and for the modified far wake portions of the wake model. This wake model provides a generally acceptable balance between accuracy and computational time.

Most of the overseas organisations visited have wake models similar to the model shown in Figure 3. Some of these are now discussed.

In using this wake model for induced velocity calculations, staff at MBB Munich adopt a prescribed, rather than free, wake geometry to save CPU time. Though they use this model for blade load calculations, even with the prescribed wake geometry, the lengthy CPU time required prohibits its use for performance estimation. They deduce most of their performance characteristics from experimental measurements and flight data.

Landgrebe and Egolf at UTRC have been involved in rotor wake modelling over a number of years. They have developed a suite of programs of varying complexity. Some of the programs used in their recent rotor performance and blade load calculations are listed here.[1] (1) Uniform inflow based on a constant momentum value (GRP and Y200) (2) Variable inflow based on classical undistorted wake geometry (F389SR) (3) Variable inflow based on prescribed distorted wake geometry (F506) (4) Variable inflow based on a generalized distorted wake geometry (F389SR). In the latter, distorted tip vortex filaments and undistorted inboard wake filaments are used.

At Boeing Vertol, staff have developed or acquired a number of computer programs over the years to study hover/forward flight analysis and rotor/fuselage interaction. A brief description of these codes, prepared by Mr L. Dadone, are included as Appendix D in Ref. 10. The Boeing Vertol staff have both prescribed and free wake models and are involved in the development of simple vortex line wake models. VSAERO[4] (Vortex Separation Aerodynamics), developed by Analytical Methods Inc. (AMI), is gaining acceptance by major helicopter companies as a tool for modelling the flow around helicopter bodies. According to AMI, this code is considerably more efficient and versatile compared to other codes. VSAERO can be used to assess 3-D flow separation and wake impingement effects. Recently, AMI received a small contract from Boeing Vertol to demonstrate the usefulness of VSAERO in the evaluation of interaction between a tilt-propeller and a wing in the JVX program.

At NASA Langley Research Center, discussions were held with Mr. John Wilson and Mr John Berry, who have a collection of computer codes for rotor

performance prediction. They use the Generalized Rotor Performance (GRP)[11] program for forward flight performance. It can be used to evaluate either an articulated or hingeless single rotor system in forward flight or in a wind-tunnel. In the program, which was originally developed by Sikorsky Aircraft Company, the rotor inflow is assumed uniform. The program produces accurate results in the flight range above the minimum power airspeed. They have also been involved in the development of a simple rotor wake model. At present, they are converting Miller's vortex line wake geometry program [12] into a usable FORTRAN program.

Hughes Helicopters Ltd uses rotor wake models developed by Rochester Applied Science Associates Inc. (RASA)[13]. The wake geometry model is similar to the model shown in Figure 3. According to Dr. Janakiram, various improvements have been made to the original RASA program.

Dr Wayne Johnson at NASA Ames has developed a comprehensive model of rotorcraft aerodynamics and dynamics (CAMRAD). The CAMRAD program[14] has a number of wake geometry models of varying complexity. These include simple undistorted models, hover prescribed wake models based on experimental measurements, and a free wake model based on Scully's distorted tip vortex geometry and prescribed inboard vortex sheet[15].

Though the wake model in Figure 3 has been successfully applied for forward flight, its application to hovering and near hovering flight is doubtful because of the wake instability and numerical convergence problems explained below.

3.2 Simple Vortex Line and Vortex Ring Wake Geometry

In hover, there is no large uniform relative wind due to the translational velocity of the helicopter. This means that the wake is not swept away from the rotor and hence more of the wake must be considered when computing the wake geometry. It also means that wake induced velocities are the only velocities present, resulting in a greater sensitivity of the wake geometry to changes in induced velocity. This increased sensitivity leads to instabilities and slow wake convergence. In the far wake, convergence to a stable vortex geometry is very difficult to achieve and there is some evidence that the far wake is unstable in reality.

In order to obtain a better understanding of the physics of the wake geometry and its effect on the rotor wake geometry, ARL work has been directed towards the development of simpler wake models[16] as a basis for future refinement, expansion, and validation. A simple model can then be used for the bulk of the computation, with a more complex model used when warranted.

All commonly used schemes to compute wake geometry involve the treatment of free vortex movement in the flow field. The Biot-Savart relation is one of the simple ways to treat this vortex flow analysis. According to this relation, the induced velocity varies inversely with the square of the distance between a finite element of vortex wake and the point at which the induced velocity is calculated. Therefore, when computing the induced velocity at a point, the wake near the point must be treated very carefully. The wake moderately far from the point can be represented by relatively simple models, while the wake very far from the point can be neglected. Taking advantage of this principle, the rotor wake is divided into two regions, the near wake attached to the blade, and the far wake below the blade, as shown in Figure 4. The near wake is represented as a semi-infinite vortex sheet attached to the blade, and the far wake as a series of straight, infinite vortex filaments. Details of this wake model together with comparisons of resulting blade loading with flight data were published in 1979[17]. Independently, Miller[18] published a very similar wake model in 1981. It is interesting to note that, after supervising many post-graduate students involved in the development of complex free wake models over a number of years, Prof. Miller saw the need for a simple rotor wake model with important wake elements identified and simplified so that the effect of these elements could be studied free from the maze of numerical iterative processes.

RAE[19] and Westland Helicopters Ltd[20] have been involved in the development of simple rotor wake models for many years. In these models, the near wake is represented by partial rings originating at the reference blade, with the far wake represented by complete vortex rings as shown in Figure 5. Beddoes[21] recently developed a simplified vortex line model to evaluate rotor airloads and noise signatures. In this model, the portion of each turn of the spiral trailing vortex that contributes most to the induced velocity is replaced by a large straight element. Then the induced velocity is calculated at the blade reference point by positioning these straight elements at appropriate locations and adding a remainder term for the rest of the spiral turn.

At Southampton University, Azzam and Taylor[22] have been developing simple rotor wake models. In their model, the vorticity close to the blade, i.e. the near wake, is represented by straight line vortex filaments. In the far wake, the geometry of the tip vortex is prescribed using experimental measurements of Kocurek and Tangler. However, the wake below the point of maximum contraction is assumed to be stable and is allowed to expand by the same contraction rate to the full rotor radius. This model is found to predict induced power and blade loadings adequately.

The rotor wake models described above are regularly used in the evaluation of blade loads, and in rotor power calculations these models generally provide adequate engineering estimates. Some of the differences between the measured powers and calculated powers are attributed to the blade/vortex interaction phenomenon, which is now discussed.

4. OTHER RELATED AREAS

4.1 Blade Vortex Interaction

There has been a recent emphasis on the more accurate analytical simulation of blade vortex interference. For many flight regimes, the tip vortices from the main rotor blades pass very close to, or even impact, following blades. This produces a complex aerodynamic environment, which influences both the local blade loading and vortex characteristics. Several aerodynamicists have investigated this problem, but much remains to be learned of the fundamentals of this phenomenon before it can be accurately modelled. Continuing research [23] in this area concerns the nature of the blade-vortex interaction with a view to improving the blade load estimation. It has been recognised that for the accurate calculation of blade-vortex interaction, it is necessary to account correctly both for the structure of the tip vortex filament from the preceding blade and for the three dimensional flow over the reference blade, including its own vortex near wake[24].

A rotor blade and a concentrated tip vortex have an effect on each other when there is a close encounter. Rapid spanwise variations of the bound circulation on the rotor blade are generated, with accompanied changes in the

blade near the wake. A close interaction may also cause changes in the properties of the tip vortex filament. Johnson[25] has developed a lifting surface solution for the loading on an infinite, aspect ratio wing, due to an infinite, straight vortex line. The vortex line lies in a plane parallel to the plane of the wing, at a given distance below it, and at an arbitrary angle with the wing. Results of this theory are used as a correction factor in rotor blade load calculations.[14,15] The rotor blade has finite aspe ratio, the vortex line is curved and has finite length, and the plane of the vortex filament is rarely parallel to the plane of the rotor blade. Although these factors are neglected, the theory developed in reference 25 could form a basic tool for the future development of this complex problem.

The requirement for improved vortex core modelling in rotor wake analysis was addressed by Scully in Reference 15. He found that by selecting a large tip vortex core radius, calculated blade loads could be matched with measured data. However, the vortex core radius required to achieve this agreement was much larger than that observed experimentally. Cook[26] has published measurements of the tip vortex of a full-scale, one-bladed helicopter rotor hovering on a whirl tower. These measurements show almost an order of magnitude smaller core radius when compared with the core radius of a vortex behind a fixed-wing.

An ultrasonic measuring system is being developed at DFVLR, Gottingen, which will be useful for non-intrusive exploration of the flow field. This technique will be suitable for the measurement of vortices behind a rotor blade. The method is based on the measurement of the flow induced, running-time differences of short ultrasonic pulses propagating along one or two measuring sound beams. The principle involved is simple, a short ultrasonic pulse being transmitted by a sender microphone. After traversing a fixed distance, the ultrasonic pulse is picked up by a receiving microphone. If the flow has a velocity component in the direction of the path of the sound wave, the running time of the ultrasonic pulse is altered. From this measured running-time difference, with the help of a computer, the essential parameters describing the vortex geometry, i.e. position, core radius, maximum circumferential velocity, can be measured[27]. The method has the important advantage that the flow region of interest remains free of intrusive probes, and it is claimed to be much faster than conventional probes.

4.2 Ground Effect

Estimation of ground effect on helicopter rotor thrust and power at hover and forward speed has always been of some interest in helicopter operations. However, in recent years, the ground related problems have become much more important because of nap-of-the-earth (NOE) operations. Recognizing the lack of theoretical and experimental data, Sheridan and Wiesner[28] in 1977 undertook some wind tunnel testing and highlighted the importance of the ground vortex when the wheel height is less than 7.5m. More recently at Cranfield, Boyd[29] initiated research projects to gain some insight into the ground vortex position, strength, and size, as a function of rotor height, speed, and thrust. This will assist greatly in the development of simple theoretical models and in the understanding of the physical description of the flow field.

The following comment[28] on the present mathematical models to deal with the NOE flight regime still holds. "The neatly constructed theoretical world of helicopter aerodynamics, with the highly refined rotor mathematical models for hover and forward flight and the marvellously crafted computer programs will avail us nothing in the study of the low/slow NOE regime without accounting for the inflow distortions due to the ground vortex flow".

5. CONCLUDING REMARKS

Most of the helicopter research establishments visited in England, West Germany, and the USA have their own rotor wake models of varying complexity. The merits of each of these models have been reviewed, and the inadequacy of the present methods for hovering flight has been noted. It was reassuring to find that the direction of the rotor wake modelling work at ARL towards simplicity was in accord with the trend within the general helicopter community. Following discussions with other research workers, it became evident that results obtained from the models developed at ARL were acceptable in the context of realistic expectations for such a complex fluid flow problem. As a result of the visit, the author was able to formulate a much clearer idea of the areas deserving greater attention at ARL. Recent access to the Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics (CAMRAD) code, obtained by Dr N.E.Gilbert through TTCP HTP-6 as well as some specialised codes obtained by the author, should provide a strong basis for progressing the work at ARL.

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APPENDIX A

ESTABLISHMENT		CONTACTS
1.	University of Southampton Southampton SO9 5NH, UK 0703-559122	a. Prof. Ian Cheeseman b. Mr H. Azzam
2.	Westland Helicopters Ltd Yaovil, Somerset, UK 0935-75222	a. Mr. Dave Balmford b. Mr John Perry c. Dr Paul Taylor
3.	Cranfield Institute of Technology College of Aeronautics Cranfield Bedford MK43 0AL, UK 0234-750111	a. Mr E. Angus Boyd
4.	Royal Aircraft Establishment Farnborough Hampshire GU146TD, UK 24461 Ext 5108	a. Mr Peter Wilby b. Mr Colin Young c. Ms Judith Miller
5.	Messerschmitt-Bolkow-Blohm Munich 80, W. Germany 089-6000 Ext 3658	a. Mr.Gradl b. Dr Mikulla c. Mr Quentin
6.	DFVLR Gottingen Gottingen 3400 W. Germany 0551-7092286	a. Dr W. Send b.. Dr W. Wagner
7.	United Technologies Hartford Connecticut 06108 USA 203-7277358	a. Mr Anton Landgrebe b. Mr Alan Egolf

8.	Boeing Vertol Company Philadelphia Pennsylvania 19142 USA 215-5222806	a. Mr Harold Rosenstein b. Mr Leo Dadone
9.	NASA Langley Research Center Hampton Virginia 23665 USA 804-8654301	a. Mr John Wilson b. Mr John Berry
10.	Hughes Helicopters Ltd. Culver City Los Angeles, USA 213-3055107	a. Dr Ram Janakiram
11.	NASA Ames Moffett Field California 94035, USA 415-6945581	a. Mr Andrew Kerr b. Dr Chi Tung c. Dr Frank Caradonna d. Dr Wayne Johnson

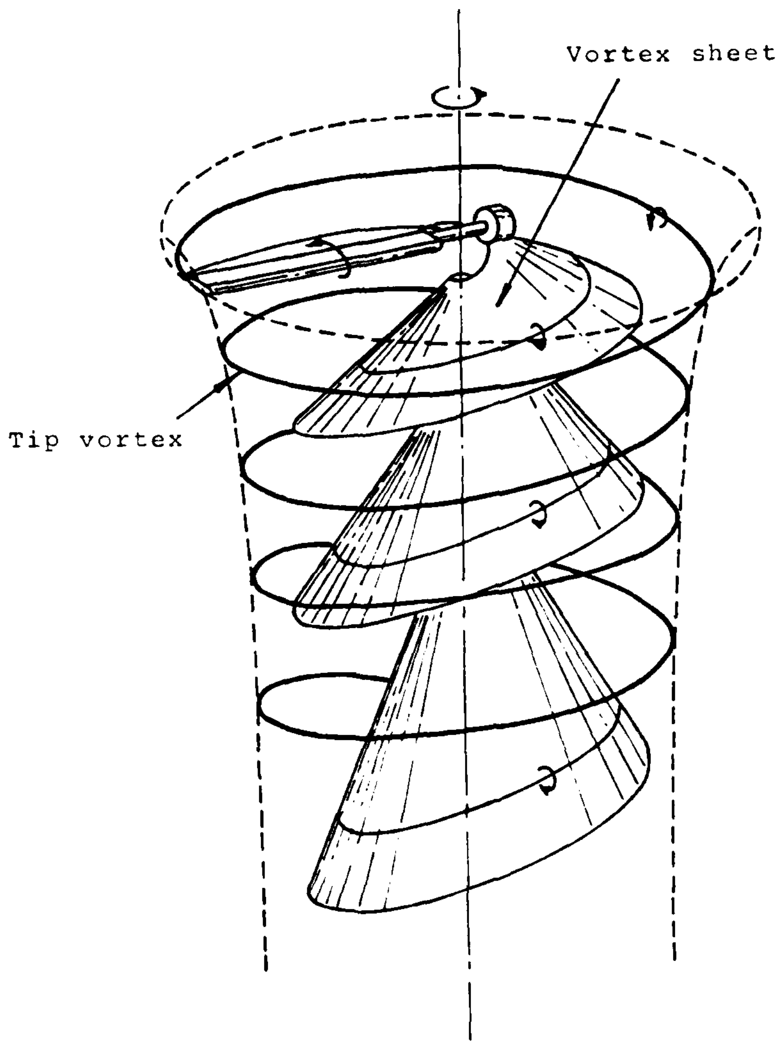

FIG. 1. ROTOR VORTEX WAKE STRUCTURE

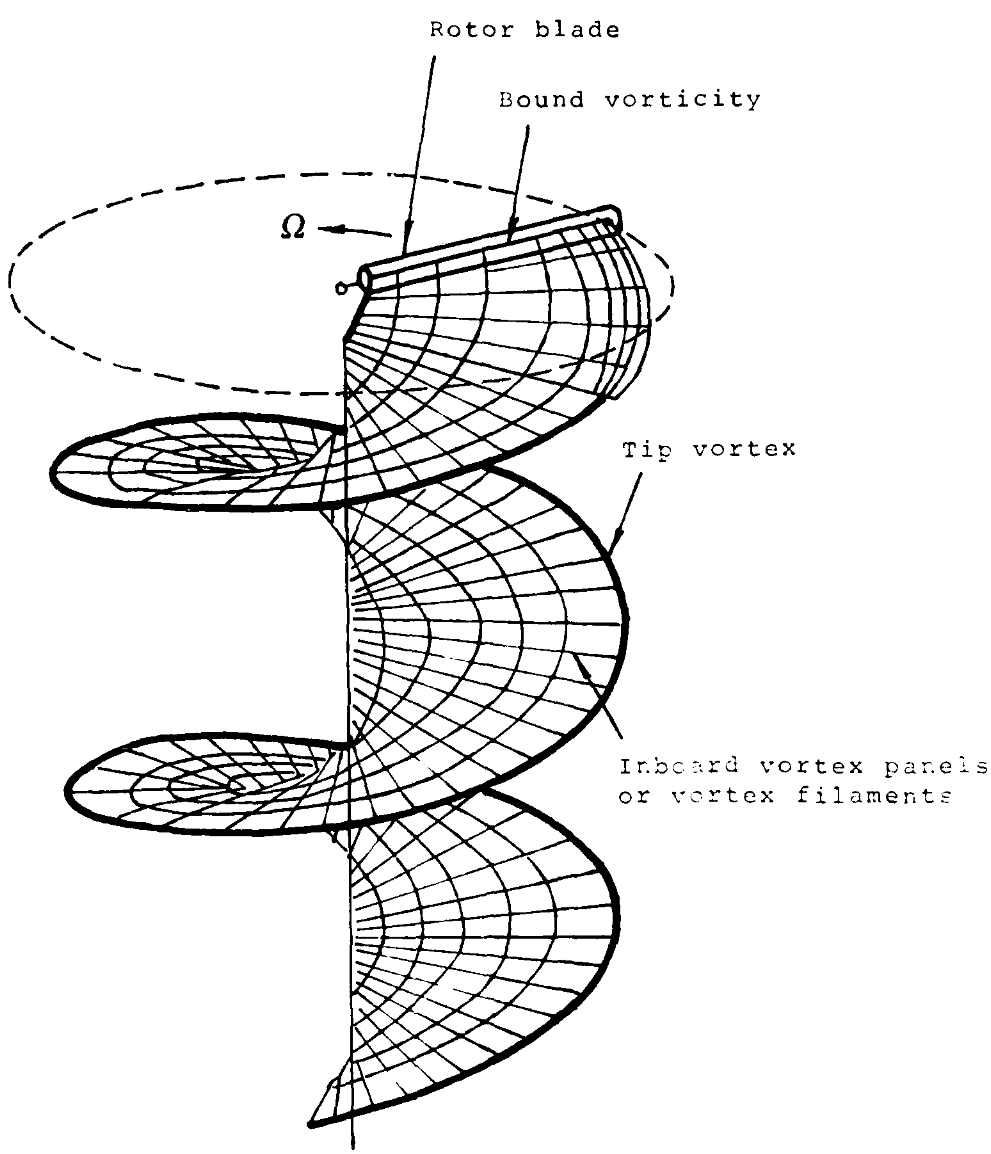

FIG. [illegible] COMPUTATIONAL MODEL FOR ROTOR WAKE ANALYSIS

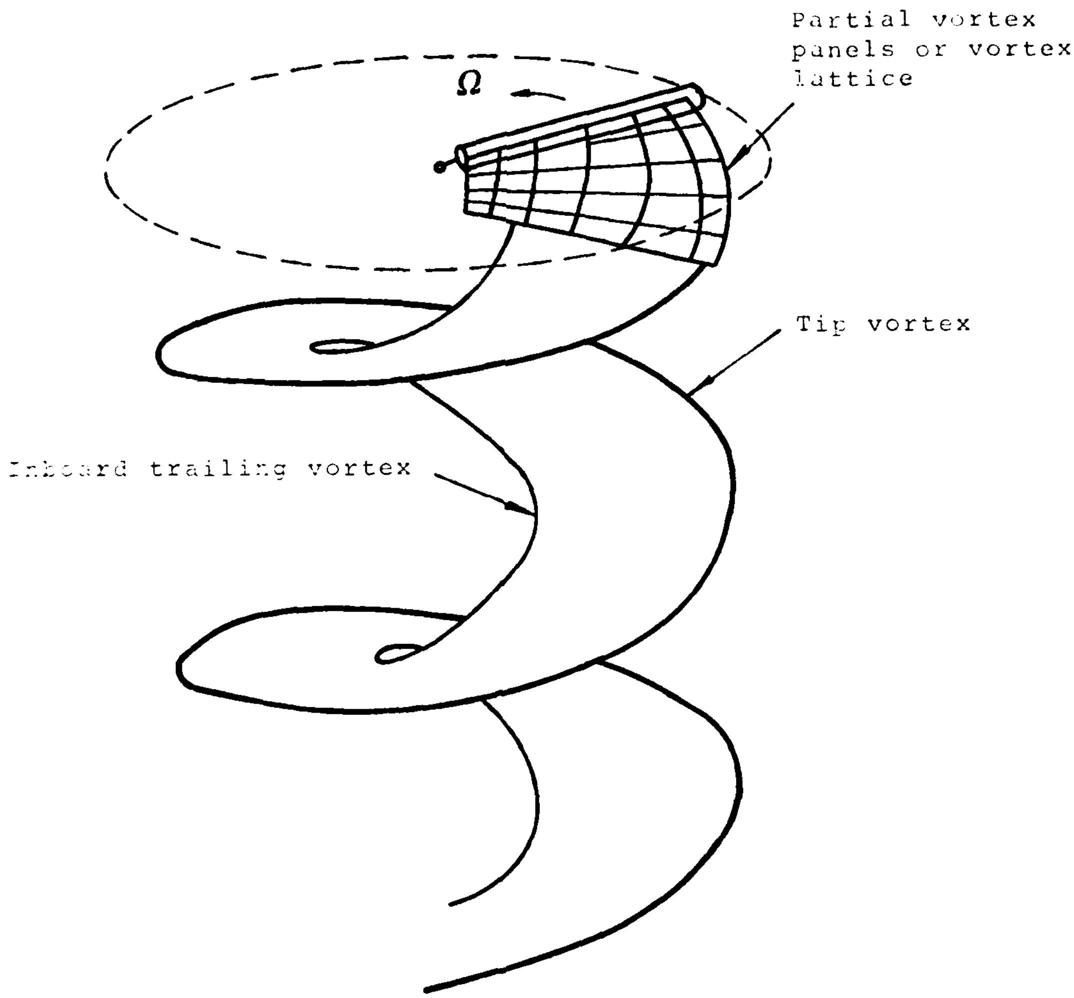

FIG. [illegible]. SIMPLIFIED FAR WAKE MODEL

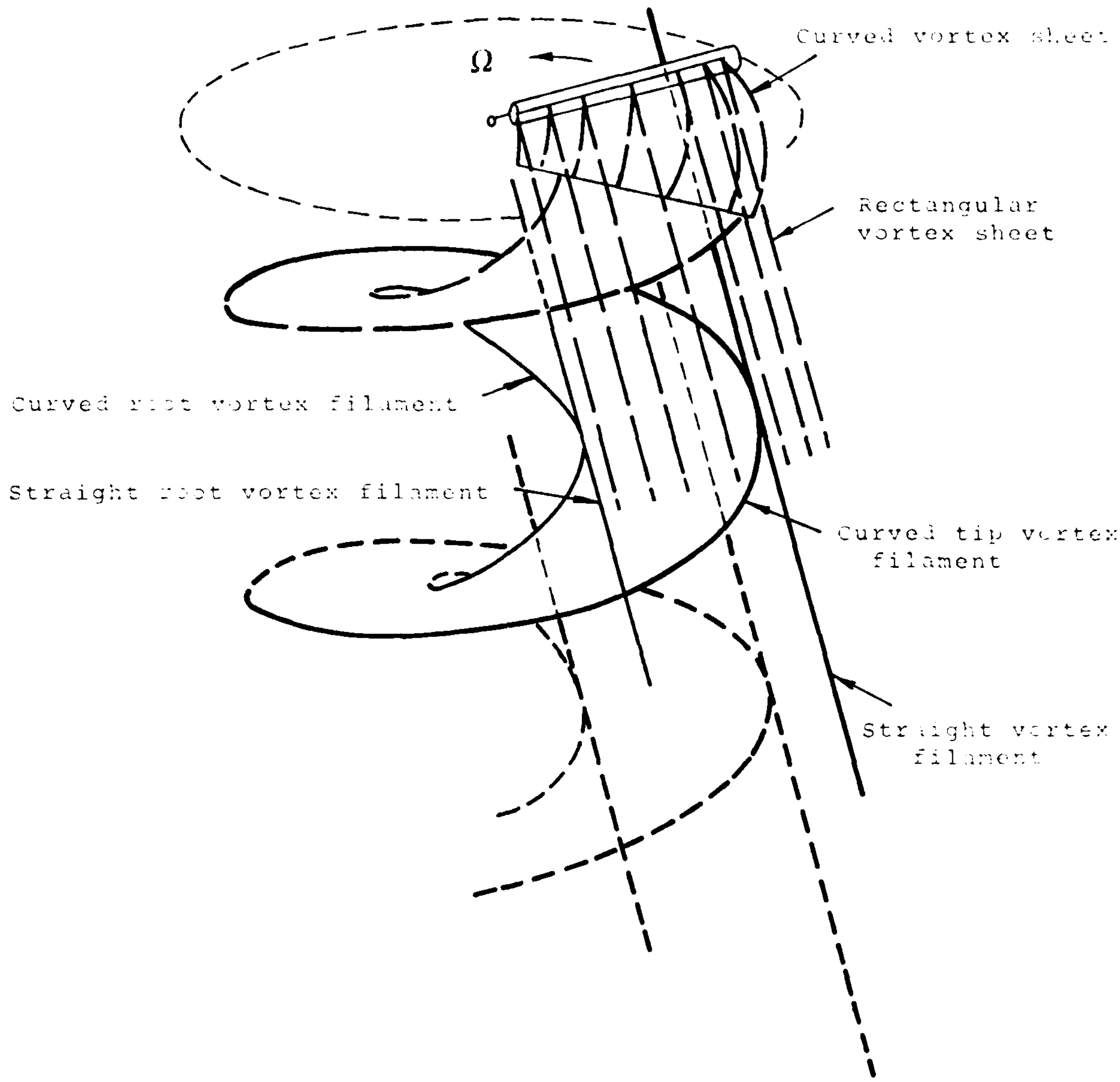

FIG.4. ROTOR WAKE MODEL IN WHICH 1) RECTANGULAR VORTEX SHEET REPLACES CURVED NEAR WAKE AND 2) STRAIGHT VORTEX FILAMENTS REPLACE CURVED ROOT AND TIP VORTICES

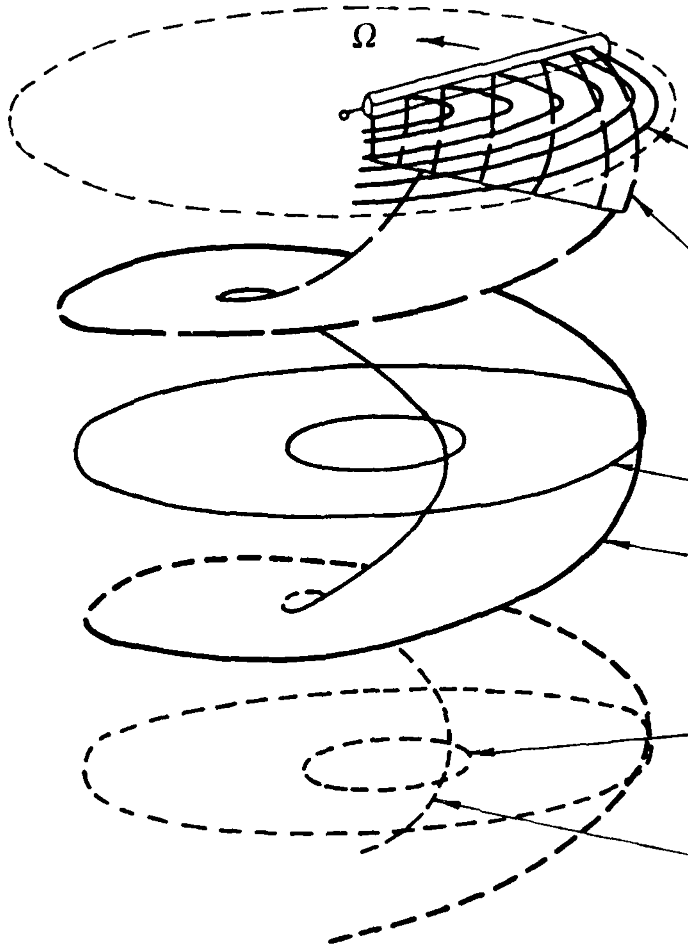

FIG.5. ROTOR WAKE MODEL IN WHICH (1) CURVED VORTEX SHEET IS REPLACED BY SEMICIRCULAR VORTEX FILAMENTS AND (2) ROOT AND TIP VORTEX FILAMENTS ARE REPLACED BY COMPLETE CIRCULAR VORTEX RINGS

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16. Abstract

Between 8th September and 9th October 1985 the author attended the Eleventh European Rotorcraft Forum in London, and visited ten research Establishments in England, West Germany, and the USA. The main purpose of the overseas visit was to investigate rotor wake modelling methods currently used. A report is given on the Forum attendance and discussions held at the establishment, together with a general review of rotor wake modelling.

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